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# RESEARCH DIRECTED TOWARD THE USE OF LONG AND INTERMEDIATE PERIOD SEISMIC WAVES FOR THE IDENTIFICATION OF SEISMIC SOURCES

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13. ABSTRACT

Seismological research supported by Air Force Contract F19628-71-C-0245 at the Lamont-Doherty Geological Observatory is summarized for the period 1 July to 31 December, 1972.

During this period work has continued on the nature and occurrence of intra-plate earthquakes - the isolated, and often high stress drop events which occur in the relatively seismically inactive interior of lithospheric plates - to reduce the chance of their misidentification as explosive events. Complimenting this study is the work on the Blue Mountain Lake earthquake swarm where a close look at the source region of some intra-plate events has revealed premonitory velocity changes. The nature of the earthquake source is also being investigated experimentally using strong-motion records and theoretically by modelling the kinematics and dynamics of shear failure.

The effect of the propagation path on seismic signals is being extended to include lateral inhomogeneities and the effects of anelastic attenuation. The horizontal refraction of surface waves has been treated theoretically, and observations of mantle surface waves have defined usefully distinct velocity models for different tectonic provinces.

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| lithospheric plate | | | | | | |
| earthquake swarm | | | | | | |
| Rayleigh wave | | | | | | |
| nodal plane | | | | | | |
| focal mechanism | | | | | | |
| $v_p/v_s$ | | | | | | |
| hydrofracture | | | | | | |
| Love wave | | | | | | |

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by

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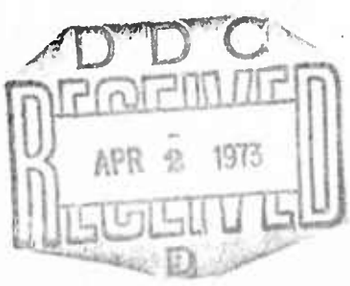

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AFCRL Project Scientist and Phone No.
Carlton E. Molineux/ 617 861-3665

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## MAJOR SCIENTIFIC ACCOMPLISHMENTS

Work during the first quarter of the period of this report was suspended at the request of Air Force Cambridge Research Laboratories. In the following paragraphs, scientific accomplishments for October thru December 1972, are summarized following the itemization in the statement of work of this contract.

### Line - Item 1a

Operation of the Lamont-Doherty network of three long-period and intermediate-period seismographic stations (the Palisades, Sterling Forest, and Ogdensburg) has continued during the last six months.

### Line - Item 1b

Sykes and Sbar have been making an extensive study of intra-plate earthquakes, those shocks that occur within large lithospheric plates. They may be contrasted with the more numerous earthquakes that occur along major plate boundaries defined by island arcs, strike-slip faults and mid-ocean ridges. Intra-plate earthquakes, however, are fairly common, particularly in North America and in Asia. It is these lone type of events within areas that are not normally thought of as highly seismically active that must be identified as earthquakes and not become "false alarms" by misidentification as possible underground nuclear explosions. Many of these events appear to be enriched in the high-frequency part of the spectrum. A preliminary analysis would indicate that they fall near the extremity of the earthquake population on an $M_s$-$m_b$ population and that they do not fall in the explosion population. We intend to examine these aspects of intra-plate earthquakes more thoroughly. Clearly it is events of this type, and especially anomalous events like the Tibetan earthquakes that fall near the explosion population, that should receive the greatest scrutiny in the discrimination-detection program.

We find that focal mechanisms can be obtained using WWSSN data for intra-plate earthquakes down to about magnitude $m_b$ 5.0 to 5.2. For events of this size a long-period P wave is usually not discernible on the standard WWSSN long-period records and hence, first motion cannot be obtained on a long-period basis. Nevertheless, very reliable first motions can be read from the short-period records. The reason for this appears to be the relatively small source size for which the short-period instruments see the focal region as essentially a point source. Consequently such events are relatively rich in short-period energy. There are two possible reasons for the increase in short-period energy. These would be a high-stress drop during the earthquake or a high Q through the crust and upper mantle beneath the source. We feel that the latter is probably the most important effect, since the ray paths near the source traverse material through the crust and upper mantle that is not young or heated or involved in recent tectonism like those of earthquakes along many plate boundaries.

Most of these shocks can be identified as earthquakes from the amplitude variation of their radiation pattern, both that of the short-period P waves and of the Rayleigh waves. For stations at teleseismic distances the closer

stations are often near one of the two nodal planes, while stations at great distances and even at PKP distances record relatively large P waves. An examination of records from stations in the distance range 30° to 40° would indicate that the P wave might be too small to yield a reliable focal mechanism solution. Nonetheless, for many of the intra-plate earthquakes for which the axis of maximum compression is nearly horizontal, the maximum radiation for P waves is nearly vertically downwards. Hence, very distant stations record very large short-period P waves compared to those of closer distances. This pronounced amplitude effect, of course, is not observed for nuclear explosions, but is related to the focal mechanism of the earthquake.

Focal mechanism solutions have been obtained for about 30 intra-plate earthquakes. By far the most dominant type of solution involves thrust faulting. Most of the world's seismograph stations receive compressions for these events, but a few stations almost always record well-defined dilatations, or other stations can be identified as being near the nodal plane from their P wave signatures. Most of these events are pbobably quite shallow.

We are undertaking an analysis of the radiation pattern of Rayleigh waves from this series of intra-plate earthquakes. For a few of the larger intra-plate earthquakes other investigators have shown that the radiation pattern for Rayleigh waves has two lobes with the maximum along the P axis. The use of Rayleigh waves will permit an accurate determination of the trend of the P axis, and it should provide additional evidence that these events are, in fact, earthquakes and not explosions. A more detailed analysis of the spectrum of the P wave of intra-plate earthquakes is also underway.

Line - Item 1c

A study for several possible criteria for forecasting the locations of large shallow earthquakes of the near future along major plate boundaries, and for assigning a crudely determined rating to those forecasts has been conducted. This study will provide useful information about optimum siting of seismic stations and networks in reference to potential earthquake risk.

These criteria are based on the past space-time pattern of large earthquakes, the lateral extent of their rupture zones, and the direction of rupture propagation. The criteria are applied in two stages. Application of the first set of these criteria to major plate boundaries along the eastern, northern, and northwestern margins of the Pacific from Chile to Japan and also to the Caribbean loop east of about 74°W results in delineation of several areas of special seismic potential along each of the boundaries. The phrase "special seismic potential" is used in this study only to indicate those segments of plate margins that fulfill certain specific criteria. However, if the criteria are valid, at least some, and perhaps most, large shallow earthquakes of the near future within the zones examined will occur near these locations. At present, the validity of the criteria is not firmly established and profound social changes based on these predictions are uncalled for, but the forecast presented here can, at the very least, serve as a guide in selecting areas for intensive study and instrumentation prior to the occurrence of a major earthquake. In certain areas where additional information is available, the subsequent application of a second set of supplementary criteria focuses special attention on certain of the areas delimited by the first set of criteria.

Line - Item 1e

1. The earthquake swarm near Blue Mountain Lake in the southern Adirondacks has proved to be an outstanding source of detailed seismicity data. As reported earlier, the seismic activity accurately defines two fault planes reflecting large horizontal compressive stress, trending nearly east-west.

In addition, careful study of the seismograms from this region has revealed the existence of premonitory velocity changes prior to singularly large earthquakes. The premonitory changes (up to 13%) in the velocity ratio of P and S waves ($v_p/v_s$) reported earlier for two BML events (M = 2.5 and 3.3) are confirmed by similar changes (up to 10%) prior to another BML earthquake (M = 3.1). To better understand these anomalous changes in $v_p/v_s$ and the focal processes prior to the mainshock, the pre-earthquake period is divided into three periods: A) normal $v_p/v_s$; B) decrease in $v_p/v_s$; and C) subsequent increase in $v_p/v_s$. A general gradual increase in microearthquake activity observed during C is in agreement with the 'dilatancy-fluid flow' model which explains the anomalies in $v_p/v_s$. A minimum in activity over a broad interval between B and C may represent dilatancy hardening. Composite fault plane solutions and spatial distribtuion of hypocenters show time dependence and appear to be related. Variations in composite fault plane solutions are similar to those reported by Nersesov and Simbireva for the Garm region. We infer that stress is not uniform throughout the focal region, and suggest that time variant stress may provide another means of predicting earthquakes.

2. Earthquakes that originate from high stress regions are the ones most likely to have relatively strong high frequency content, and these events are of special interest because they are the most likely ones to be confused with explosion signals.

As reported earlier northeastern North America is a region of high compressive stress. The maximum compressive stress trends east to northeast over an area extending from west of the Appalachian Mountain system to the middle of the continent, and from southern Illinois to southern Ontario. In this region, earthquakes appear to occur in regions of high stresses along weak zones in the lithosphere. An example of such a weakness is the seismic belt trending from Boston to the northwest through Ottawa.

In conjunction with detailed seismicity studies in apparent weak zones within the region of high stress and in situ stress determinations by hydrofracuuring we have observed seismic activity associated with hydraulic mining in western New York State. For the past 2.5 years we have monitored the seismicity of western New York State and in particular the "hot spot" of natural activity near Attica and Dale. In 1971 we noticed a sharp increase in seismicity after high pressures were attained at a hydraulic mining operation in Dale. This fact, the closeness of the events to the wells, and the near cessation of activity

after the injection well was shut down indicate a causal relationship between the high pressure fluid injection and seismic activity. In August 1972 a second well was hydrofractured and subsequently used as the injection well of the salt recovery operation. However, only a few events occurred near the well used in 1972. The hydrofracture and pressure histories of the 1971 and 1972 injection wells were nearly identical. The two wells, 0.5 km apart, are 0.5 km deep and both bottom near the Clarendon-Linden fault, a major feature which extends for at least 150 km. The 1972 well was hydrofractured near the middle of the salt layer, whereas that in 1971 was hydrofractured near its base. The water loss in 1971 was appreciable, but that in 1972 was negligible. The differences in seismic activity and water loss are consistent with the hypothesis that fluids and thus high pore pressures were confined to the salt layer in 1972 but into the fault zone in the rock unit below the salt.

3. The time history of displacement on opposite sides of the fault during the Parkfield, California earthquake of June 27, 1966 has been modeled. Data used are ground displacement obtained by double integration of accelerograms recorded at five sites near the southeastern end of rupture. Ground displacement to compare with the data have been computed as if each of these sites were located in an infinite homogeneous space and the rupture were a smoothly propagating ramp. Reasonable agreement is obtained on most horizontal components before the arrival of surface waves. The best fitting model has a well controlled propagation velocity of 2.8 to 3.0 km/sec, but allows any particle velocity on the fault surface greater than 10 cm/sec

4. Earthquakes are the immediate result of some rupture process, which spreads rapidly in time over a zone in which stress has previously been slowly accumulating. Evidence on the kinematics of this rupture process is available from geological and engineering field studies, from distribution of the first motions radiated by the source, and from our understanding of large-scale tectonic motions. Such studies all indicate that the earthquake mechanism commonly involves shear failure across a planar fault surface.

Motions at and near an earthquake source are investigated theoretically and numerically. The source is modeled by a crack across which the shear stress is dropped to some constant times the normal stress: the crack nucleates from a point, and then grows steadily as an ellipse with fixed eccentricity. The solutions allows rapid computation of the accelerations radiated, at all points in space and time. At about 1 km from the fault surface, but 10 km from the point of initial rupture, accelerations reach up to about 1/2 g (per 100 bars of stress drop) as the rupture front passes nearby. The description of earthquake source motions satisfies both the kinematic and dynamic requirements of shear failure on a plane fault surface.

Line - Item 1f

1. Horizontal refraction of Love waves.

The seismic surface wave magnitude is dependent on the transmission and reflection of the surface waves at the continental margins. Love wave transmission and reflection is investigated theoretically. The transmission and reflection coefficients are found to be strongly dependent on the period of the Love waves. In models of a continental margin the outgoing Love wave has for some periods a larger amplitude than the incoming Love wave. A simple explanation is, that a Love wave to contain the same energy density in a less rigid medium will have to have larger amplitudes than a Love wave in a more rigid medium.

The Love wave transmission and reflection dependence on the angle of incidence is qualitatively similar to the dependence found for propagating rays of elastic waves.

The method views the Love wave as a super-position of SH rays, that are constructively interfering in a layer, and inhomogeneous SH rays propagating horizontally in the half space below.

The vertical boundary conditions in the continental margin model are satisfied exactly. The horizontal boundary conditions will give rise to diffracted waves, dependent on period, model and angle of incidence. Since most of the energy is in the Love waves the coupling of the diffracted waves into the Love waves is considered to be minor.

2. Attenuation plays an important role in the transmission of body phases through island arc and trench regions and through the low velocity zone. Recent theoretical work on attenuation by Strick and others predicts that the pulse or wavelet, in addition to being broadened and depleted of high-frequency components as expected, is also dalayed. This theoretically predicted delay is not insignificant (amounting to as much as 20% of the travel time for media such as plexi-glass) and, if true, could require important correction of travel time tables as well as modification of existing models of the lithsophere in island arc regions.

The reality of this theoretical delay is being investigated mumerically. It has been found to depend, paradoxically, on the behaviour of the attenuation model at the very highest frequencies - frequencies for which the transmission of energy is negligible. This baffling fact is a direct result of the formal constraint that the body-wave arrival be causal. Since attenuation is, at some level, related to thermal dissapation which can propagate -- formally at least -- with inifinte velocity, we are investigating the possibility of permitting some mildly non-causal propagation to remove the intuitively objectionable predicted delay.

## LIST OF PERSONNEL

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Graduate Students:

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Engineers:

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Problems Encountered

None

Fiscal Status

Estimated expenses through the close of the present contract period: $198,688

Total cost to completion of contract: 278,316

Action Required by the Government

None

Future Plans

Future plans call for the continuation of the research outlined above and in other areas specifically related to the VELA-UNIFORM program.

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Very truly yours,

Lynn R. Sykes

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